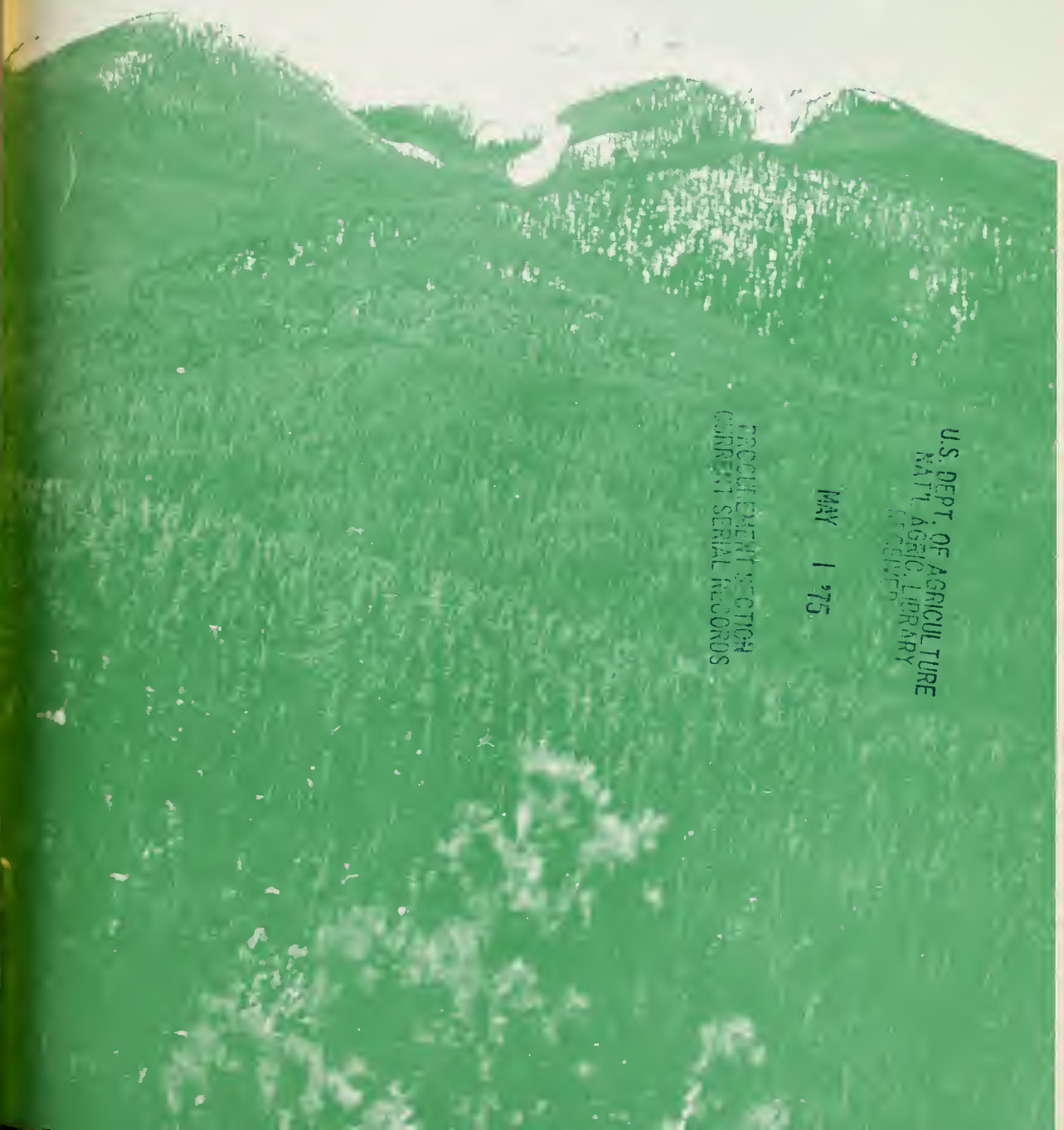
USDA Forest Service
Research Paper RM-133
February 1975

Rocky Mountain Forest and
Range Experiment Station
Forest Service
U.S. Department of Agriculture
Fort Collins, Colorado

SIMULATING TIMBER YIELDS AND HYDROLOGIC IMPACTS RESULTING FROM TIMBER HARVEST ON SUBALPINE WATERSHEDS

by Charles F. Leaf
Robert R. Alexander



ABSTRACT

A dynamic simulation model which has been specifically designed to determine the hydrologic changes resulting from timber harvesting and correlary models which simulate timber yields are described. Emphasis is placed on the "planning unit" which is defined by environmental characteristics, including combinations of slope, aspect, elevation, and forest cover. The models are intended for use on subalpine watersheds where the primary source of streamflow is from melting snow. The hydrologic model simulates winter snow accumulation, the short- and longwave radiation balance, snowpack condition, snowmelt, and subsequent runoff in time and space. The timber models simulate projected timber yields in response to changes in cultural treatments and/or variations in original stand and site conditions.

The models are capable of simulating a broad array of timber harvesting alternatives. Hydrologic changes and timber yields can be determined for intervals of time which can vary from a few years to the rotation age of subalpine forests (120 years and longer). In the hydrologic model, this is accomplished by means of time trend functions which compute changes in evapotranspiration, soil water, forest cover density, reflectivity, interception, and snow redistribution as the forest stands respond to management.

The models have been used to simulate the effects of forest and watershed management on several representative drainage basins in the Rocky Mountain Region of the United States. Projected hydrologic changes and growth and yield subsequent to timber harvesting in lodgepole pine and spruce-fir are described in this report.

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Charles F. Leaf, Principal Hydrologist
and
Robert R. Alexander, Principal Silviculturist

Introduction

Watershed management research during the past 50 years has shown that subalpine forests exert a significant effect on water yields. Hence, man-caused changes in the forest environment can be expected to affect the water resource. When timber is harvested, the magnitude of the resulting hydrologic change is highly sensitive to the pattern in which a given volume of wood is removed.

Because water from snowmelt is a primary resource in the Rocky Mountain Region of the United States, the need for a planning tool to evaluate the potential hydrologic effects of various timber harvesting strategies is obvious in view of the U.S. Forest Service goal of sound multi-resource management.

Some progress has been made in the development of dynamic simulation models which predict the short-term effects of timber harvesting on snowmelt and water yield (Leaf and Brink 1972, 1973a, 1973b). This work has recently been expanded to determine the long-term interactions between the water and timber resources with regard to initial partial cutting in old-growth subalpine forests, and subsequent management of these stands.

The system described in this report utilizes output from a water balance model (Leaf and Brink 1973b, 1975) to simulate both the immediate and long-term effects of forest and watershed management, in areas where runoff is derived primarily from melting snow. Considerable flexibility is provided for simulating alternative silvicultural systems. Moreover, yield tables can be produced which show how projected timber volumes will vary in response to various timber management alternatives (Myers 1971).

The hydrologic model is described first, followed by examples of projected hydrologic changes from timber harvesting on two watersheds in Colorado and Wyoming. A discussion of the timber models, which simulate growth and yield once old-growth subalpine forests are converted to managed stands is also presented. The models simulate stand growth and response to intermediate cuttings from the regeneration period to final harvest for timber production. Finally, examples are given which illustrate how the models can be used simultaneously to provide the manager with multi-resource response data for timber and water.

Hydrologic Model

Model Configuration

The analytical framework of the system is based on a "planning unit" which is defined by environmental characteristics including combinations of slope, aspect, elevation, and the species, form, and structure of the forest cover. The model is designed to simulate the hydrologic effects of timber harvesting in order to develop management strategies for planning intervals which can vary from a few years to the rotation age of subalpine forests (120 years and longer).

Management strategies may subdivide a given planning unit into as many as eight distinct areas or "response units," which may be managed independently at varying points in time during the planning interval. Provision is also made so that different cutting practices may be imposed on the response units, and finally, any number of cuttings may be made on a given response unit at specified years during the planning interval.

Hydrologic integrity is maintained as management strategies are formulated, since all interactions between the various response units are accounted for in time and space. The interactive effects of a new decision on ones previously implemented are simulated, as are the effects of time, as demonstrated through reforestation. Moreover the overall hydrologic effects resulting from each management decision on the planning unit are projected to the end of the planning interval as though it were the final decision in the strategy. Thus, the singular effects of each decision can be evaluated.

A core model simulates the water balance on a daily basis. On those areas where forest cover has been removed, the parameters which define soil water availability, forest cover density, reflectivity, interception, and snow distribution are adjusted on an annual basis by means of time-trend relationships described later in this report.

Because climatological observations are rarely available for the long periods of time simulated, the system has the capability to extend a sample data base by a randomized selection of water years until the desired planning interval is completed.

Theory

The discussion which follows is necessarily brief and intended to give the reader a general idea of the scope of the model. Detailed flow chart descriptions and more complete hydrologic theory have been published by Leaf and Brink (1973a, 1973b, 1975). The reader is referred to these publications for a more comprehensive treatment of the concepts which follow. At the present time, the model is being used in selected areas throughout the Rocky Mountain Region. A flow chart of the core model in the system is shown in figure 1. Figure 2 shows how the core model is used in executing alternative management strategies.

Snowmelt. — Previous work in high-elevation coniferous forests has shown that radiation is the major source of energy for snowmelt. Accordingly, short- and longwave radiation represent the energy components available for snowmelt. Shortwave radiation to the snow or ground surface beneath the forest canopy is controlled by a transmissivity coefficient to be discussed later, and which varies according to forest cover characteristics. The incident shortwave radiation as measured on a horizontal surface is adjusted according to the slope and aspect of each hydrologic response unit. Longwave radiation is computed by the Stefan-Boltzmann equation.

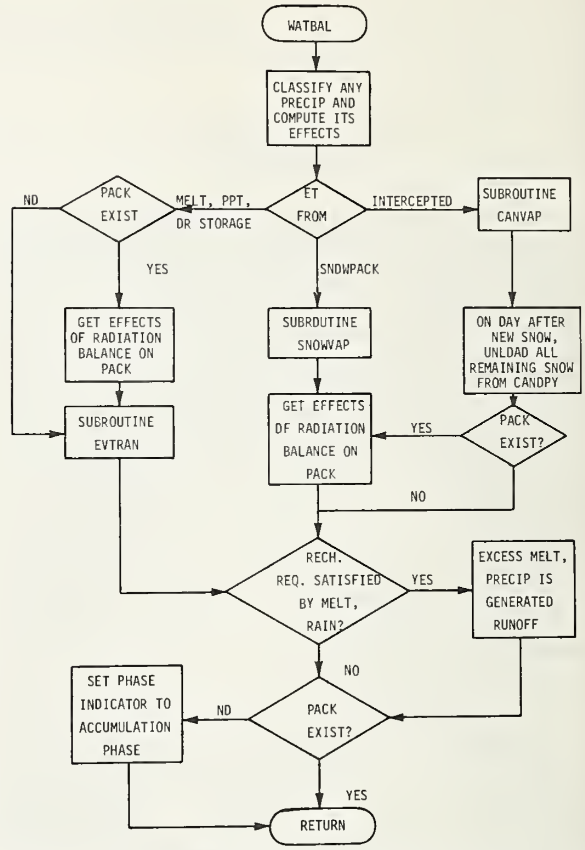


Figure 1. — Flow chart showing system core model.

Snowpack reflectivity is varied according to precipitation form, air temperature, and the energy balance. During the winter months, temperatures within the snow cover are simulated using unsteady heat flow theory. The snowpack will yield melt water only when it has become isothermal at 0°C, and its free water holding capacity is reached.

The generalized equation for snowmelt can be written as:

$$M = S_W(1.0 - R)T + C_d(\sigma T_a{}^4 - \sigma T_s{}^4) + (1.0 - C_d)(\alpha\sigma T_a{}^4 - \sigma T_s{}^4) \qquad [1]$$

where

M = Daily snowmelt in calories per cm^2,

S_W = Incoming solar radiation in ly per day;

R = Reflectivity of snowpack, expressed as a decimal;

T = Shortwave radiation transmissivity coefficient, expressed as a decimal;

C_d = Forest cover density, expressed as a decimal;

σ = Stefan-Boltzmann Constant;

T_a = Air temperature in °K;

T_s = Snow surface temperature in °K;

α = Coefficient for computing sky radiation, expressed as a decimal. On clear days, $\alpha = 1.00$.

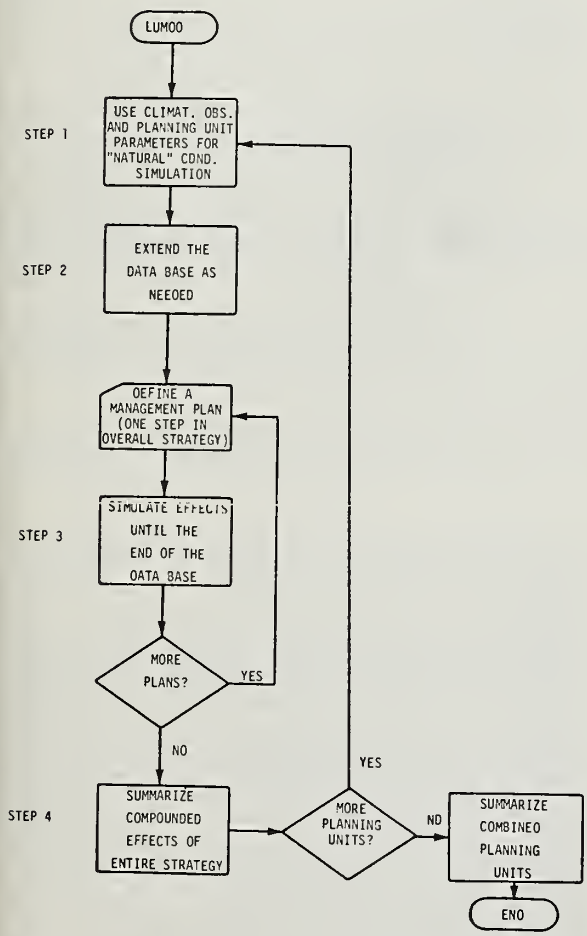


Figure 2. — Flow chart showing how core model is used to execute alternative management strategies

Evapotranspiration. — A "potential" evapotranspiration function was developed for the model based on the empirical Hamon equation (Hamon 1961), which requires latitude, converted to day length; and mean monthly temperature, converted to saturation vapor density. The coefficient, C, in Hamon's equation was modified in order to obtain an expression for potential evapotranspiration, E_S under "unlimited" solar input, assumed herein as potential radiation. The evapotranspiration computed by this expression is reduced in proportion to the radiation actually received each day according to the expression:

$$E_s = (C'D^2p_t)(\frac{SW}{P}) \qquad [2]$$

where

C' = the modified coefficient defined above,

D = possible sunshine in units of 12 hours,

p_t = saturated water vapor density (absolute humidity) at the daily mean temperature in grams per cubic meter,

SW = daily shortwave radiation in langleys, and

P = potential shortwave radiation for the day as computed by Frank and Lee (1966).

The adjusted evapotranspiration is then redefined according to its source, which can include: (1) evaporation from snow intercepted by the forest canopy; (2) evaporation from the snowpack surface; and (3) evapotranspiration during the growing season.

Input to the watershed system is derived from snowmelt and rainfall. Once evapotranspiration requirements have been satisfied, any remaining input is used to satisfy soil water recharge requirements. When field capacity is reached, the residual input becomes water available for streamflow (generated runoff).

With regard to evapotranspiration, it was assumed that water use by old-growth forest during the growing season proceeds at rates limited only by available energy until the soil water is depleted to 50 percent of the maximum "available" for transpiration (field capacity index). Thereafter, transpiration is decreased in proportion to the amount of soil water below one-half of the field capacity

index. In open or cutover areas, it was reasoned that the absence of dense vegetation and a shallow rooting depth enables evapotranspiration to proceed at maximum rates only when the soil mantle is completely recharged. Thereafter, evapotranspiration is linearly decreased to zero at an assumed three-fourths of the field capacity index. These relationships are shown graphically in figure 3a. As forest vegetation reoccupies cutover areas, and consumptive use is increased, the

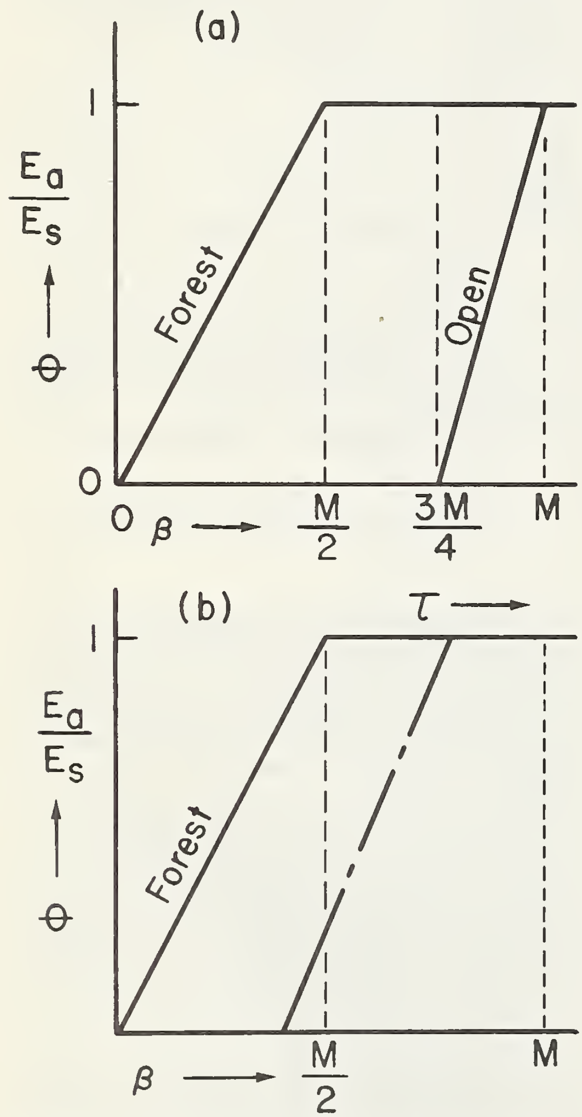


Figure 3. — Evapotranspiration as a function of available soil water for: (a) old-growth forest and open conditions, and (b) old-growth forest and some intermediate forest cover condition several years after timber harvesting.

relationship in figure 3a changes until ultimately, as the forest cover is reestablished, it approaches that of the old-growth forest curve. It is this phenomenon which is primarily responsible for diminishing water yield increases over time following timber harvest. The rate at which this transition takes place depends upon forest species, climate, stand conditions, and the objectives of management.

A general expression for the relations shown in figure 3 can be written as follows:

$$\theta = \Delta\left[\beta - \left(\tau - \frac{1}{\Delta}\right)\right] = \Delta\left(\beta - \tau\right) + 1$$

$$\beta > \tau,\ \theta = 1$$

$$\tau - \frac{1}{\Delta} < \beta < \tau$$

$$\beta < \tau - \frac{1}{\Delta},\ \theta = 0 \qquad [3]$$

where

θ = the ratio, $\frac{E_a}{E_s}$. E_a is the evapotranspiration rate adjusted for available soil water, and E_s is computed in this model by a modified version of the Hamon equation.

β = the available soil water at any time during a given water year. $0 \leq \beta \leq M$ where M is the "field capacity index,"

τ = the critical point at which available soil water begins to limit evapotranspiration. $M/2 \leq \tau \leq M$, and

Δ = the slope of the relationship between $E_a/E_s = 0$ and 1.

It appears from the Fool Creek watershed study in central Colorado that hydrologic changes resulting from timber harvest in the subalpine zone persist for many years. The Fool Creek study showed that water yield increases did not decrease significantly more than 16 years after treatment (Hoover and Leaf 1967). These results and results from timber management research were used to develop the time-trend relationships discussed below. As seen below, the procedure used in formulating each time-trend relationship was to: (a) establish plateaus, and maximum and minimum values for each hydrologic variable; (b) establish critical times at which a transition begins to occur; and (c) assume a functional relationship which determines all intermediate values.

It should be emphasized that, due to a lack of understanding of long-term hydrologic phenomena, the time-trend equations are not exact in any intrinsic or mathematical way (Forrester 1961). They should be considered only as relationships which represent rational estimates of how the most significant processes vary over a long period of time. These time-trend relationships are logically plausible, but additional research is needed before more precice equations can be developed.

Soil Water. — The critical point at which available soil water begins to limit evapotranspiration (τ), was assumed to vary with time and forest tree species. These relationships were expressed as

$$\tau = Me^{-k(t - t_{c_1})} \qquad \tau = M, t \leq t_{c_1} \qquad \tau = M/2, t \geq t_r \qquad [4]$$

where
k = an index of the rate of decline of τ
t_{c_1} = the time at which available soil water begins to limit evapotranspiration in years, and
t_r = the time at which the hydrologic effect of timber harvesting becomes insignificant.

The parameters, k and t_{c_1}, vary according to tree species. The assumed relationship between Δ and τ is given by

$$\Delta = \frac{4\tau}{M^2} \qquad [5]$$

Substituting equations [4] and [5] into equation [3] yields

$$\theta = 4e^{-k(t - t_{c_1})}\left[\beta/M - e^{-k(t - t_{c_1})}\right] + 1 \qquad [6]$$

which is a general equation for θ as a function of forest cover type, field capacity index, and time.

Forest Cover Density. — Forest cover density plays an important role in the simulation model. It is the major descriptive parameter of the form, structure, and arrangement of forest stands, and therefore controls the energy balance, interception, and evapotranspiration. This parameter is also related to basal area which is pertinent to timber production, as discussed later. Forest cover density as used in the model is not defined as "canopy" or "crown" closure, but rather as a tree parameter which integrates the net effects of the overstory on the transmission of solar radiation to the forest floor. Forest cover density varies according to crown closure, the vertical foliage distribution, species, season, and stocking (Reifsnyder and Lull 1965). Empirical relationships between various timber stand variables and percent radiation beneath the forest canopy (transmissivity coefficient) have been derived for the three major subalpine tree species in the process of model calibration and from solar radiation transmission studies in central Colorado. The resulting equation from this work is given by

$$T = 0.19\, C_{dmx}^{-0.6} \qquad [7]$$

where
T = the transmissivity of the forest canopy expressed as a decimal fraction of the amount of solar radiation available above the forest canopy, and,
C_{dmx} = the natural old-growth forest cover density expressed as a decimal.

Combinations of C_{dmx} and T for the three major subalpine forest species are given in Leaf and Brink (1975).

As trees reoccupy cutover areas, forest cover density (C_d) increases with time until it reaches a maximum value. Research has shown that the rate at which forest cover density reaches this plateau depends on environmental conditions, stocking levels, and species. In subalpine coniferous forests in the Rocky Mountains, it can vary from 30 to more than 80 years (Alexander 1974). Accordingly, C_d was assumed to vary as a function of time according to the following equation:

$$C_d = \frac{C_{dmx}}{\Phi^2}\left(t - t_{c_2}\right)^2 \qquad t_{c_2} \leq t \leq \Phi \qquad [8]$$

where
C_d = intermediate forest cover density expressed as a decimal
Φ = the time in years from t_{c_2} at which maximum forest cover density (C_{dmx}) is reached, and
t_{c_2} = critical time at which regeneration is sufficient to reestablish the stand. When $t \leq t_{c_2}$, $c_d = 0$.

Reflectivity. — Studies of the energy balance and associated vapor loss indicate that the major variations with regard to latent heat flux are associated with reflectivity (Baumgartner 1967). Accordingly, a relationship between reflectivity and forest cover density was derived as follows:

$$R_f = R_{fo} \exp \left[\frac{-\omega C_{dmx}(t - t_{c_2})^2}{\Phi^2} \right] \qquad [9]$$

where

R_f = the reflectivity of the forest stand,
R_{fo} = the reflectivity of a forest opening (assumed herein as 0.5). When $t \leq t_{c_2}$, $R_f = 0.5$, and
ω = $1.609\, C_{dmx}^{-1}$.

Equation [9] is used to adjust equation [6] for net available energy.

Thus:

$$\theta' = \frac{E_a'}{E_s} = \theta(1 - R_f) \qquad [10]$$

where Ea′ is the actual evapotranspiration adjusted for both available soil-water and energy.

Interception. — In the interception portion of the model, it is assumed that:

1. The amount of snow intercepted varies according to forest cover density, C_d;
2. The intercepted snow rests on the canopy for only 1 day following the day of the snow event due to turbulent winds which remove snow from the crowns; and
3. The residual intercepted snow which is not vaporized after that period of time is added to the snowpack.

The second and third assumptions are based on field studies which indicate that snowfall is strongly influenced by wind interacting with the forest and local topography (Hoover and Leaf 1967, Hoover 1969).

Evaporation from the snow surface and from snow intercepted by the forest canopy is computed by the following rational relationships (Leaf and Brink 1975):

$$V_s = (1 - C_d)E_s \qquad [11]$$

$$V_c = \frac{1}{C_d} E_s \qquad C_d \geq \frac{C_{dmx}}{2} \qquad [12]$$

where
V_s = evaporation from the snow surface
V_c = intercepted snow evaporation,
C_d = intermediate forest cover density as = defined in equation [8]; and
E_s = potential evapotranspiration as defined in equation [2].

When $C_d \geq \frac{C_{dmx}}{2}$, and snow rests on the canopy, evaporation is computed by equation [12], whereas during conditions when the canopy is free of snow, evaporation takes place according to equation [11]

However, when $0 < C_d \leq \frac{C_{dmx}}{2}$, and snow rests on the canopy, both equations [11] and [12] are used as follows:

$$V_t = E_s \left[\frac{2}{C_{dmx}} + \left(1 - \frac{2C_d}{C_{dmx}}\right)\left(1 - C_d\right) \right] \qquad [13]$$

where
V_t = combined evaporation from snow surface and intercepted snow in cutover areas.

Equation [13] more realistically represents the evaporation from cutover areas which are not completely occupied by trees. Equation [13] applies only when $C_d > 0$. When $C_d = 0$, $V_t = V_s$. By substituting equation [8] into equation [13] the following relationship is obtained:

$$V_t = E_s \left\{ \frac{2}{C_{dmx}} + 1 - \left[\frac{2\left(t - t_{c_2}\right)^2}{\Phi^2} \right] \left[1 - \frac{C_{dmx}}{\Phi^2}\left(t - t_{c_2}\right)^2 \right] \right\} \qquad [14]$$

which expresses V_t as a function of C_{dmx} and time.

Snow Redistribution. — Redistribution of snow as a result of patch-cutting is a significant factor influencing runoff. Moreover, in the lodgepole pine type in Colorado, this phenomenon is not greatly diminished more than 30 years after timber harvest in spite of regrowth of trees and

associated increase in forest cover density (Hoover and Leaf 1967, Hoover 1969). It is believed that changes in natural snow accumulation patterns produced by timber harvest will persist until the new crop of trees approaches the height of the remaining virgin forest. Moreover, optimum redistribution of snow results when old-growth subalpine forests are (a) harvested in small patches less than 8 tree-heights in diameter; (b) protected from wind; and (c) interspersed so that they are 5 to 8 tree-heights apart. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow on headwater basins is not significantly increased. Accordingly, the following relationships were developed for simulating snow redistribution effects with time and the three primary tree species:

$$\rho = \rho_{mx} \exp\left[-k_1(t - t_{c_3})\right] \qquad \rho = \rho_{mx}, t \le t_{c_3} \qquad \rho = 1,\ t \ge t_{r_1} \qquad [15]$$

where

- ρ = snow redistribution factor in the cutover area which varies according to the silvicultural system used.
- ρ_{mx} = the redistribution factor immediately after timber harvesting.
- k_1 = an index of the rate of decline of ρ,
- t_{c_3} = the time at which forest regrowth begins to reduce snow redistribution in years, and
- t_{r_1} = the time at which forest regrowth causes snow redistribution to become insignificant.

The parameters, k, tr_1, and t_{c_3} vary according to tree type. When $t \le t_{c_3}$, no adjustments are made in the redistribution, since field studies in the Rocky Mountain Region indicate that a correction is not warranted for several years after harvest cutting.

It should be emphasized that redistribution theory is valid only when timber is harvested in small patches (5 to 8 tree-heights in diameter) which occupy less than 50 percent of a given planning unit. An optimum redistribution factor is approximately 1.30, which corresponds to 5 to 8 H patches which occupy 40 percent of the planning unit. In this situation, the snowpack is increased 30 percent in the openings and decreased 20 percent in the uncut forest. When openings are larger, snow is scoured from the center, whereas smaller openings also do not trap snow efficiently.

Individual-tree Selection Cutting.— Selection cutting in the model corresponds to a reduction of the forest cover density (C_d). The degree that C_d is reduced depends on characteristics of the stand and the volume of timber removed. In old-growth stands, if C_d is reduced by 50 percent or less from C_{dmx}, it is assumed that forest canopy density does not increase subsequent to harvest cutting. However, if C_d is reduced more than 50 percent from C_{dmx}, equation [8] is used to simulate redevelopment of the canopy with time. Solving equation [8] for time yields:

$$t_\eta = \left[\frac{\Phi^2 C_d}{C_{dmx}}\right]^{1/2} + t_{c_2} \qquad [16]$$

If the degree to which thinning reduces Cdmx is given by η, then Cd is given by

$$C_d = C_{dmx}(1 - \eta)$$

Hence, equation [16] can be written as:

$$t_\eta = \Phi\left[(1 - \eta)\right]^{1/2} + t_{c_2} \qquad [17]$$

where

- t_η = the time required to reach the reduced forest cover density as if the stand were initially patch-cut, and
- η = the degree that C_d is reduced from C_{dmx} expressed as a decimal.

All of the time trend relationships are then initialized at t_η in order to simulate the hydrologic effects of selection cutting.

Applications

Field Studies. — Watershed studies in the Central Rocky Mountains show that timber harvesting significantly affects the hydrologic system. For example, on the 714-acre Fool Creek watershed where 39 percent of the area was clearcut in strips 1 to 6 tree-heights wide (fig. 4), snow accumulation, melt, and subsequent water yield were all affected. Hoover and Leaf (1967) report that total snow storage on Fool Creek did not

increase after harvest cutting. Strip cutting caused more snow to accumulate in the openings, however, and less in the uncut forest. When regressed against a 1,984-acre control watershed, it was determined that the average annual runoff increased more than 3 inches after treatment (fig. 5). Seasonal peak flows were not increased, nor were summer recession flows diminished (Leaf and Brink 1972). Timber harvesting caused higher snowmelt rates in early spring and more efficient water yield.

Figure 4. — Fool Creek experimental watershed, Fraser Experimental Forest. Control watershed is to the right of Fool Creek.

Model Studies of Snowmelt. — Dynamic hydrologic models are useful tools for quantifying the effects of watershed changes on runoff. We have used this procedure to study the effects of hypothetical watershed management practices on undisturbed watersheds in the Rocky Mountain Region using our best information from field studies and the model described above.

Short-Term Hydrologic Impacts of Timber Harvesting

In simulating a hypothetical timber harvest on the 667-acre Deadhorse Creek watershed in central Colorado, the snowmelt portion of the model has produced results similar to those observed from the Fool Creek experiment. Elevations on Deadhorse Creek vary from 9,450 feet msl to 11,600 feet msl. Soils are derived from gneiss and schist rocks; the forest cover is old-growth lodgepole pine and spruce-fir.

Leaf and Brink (1972) assumed that 40 percent of the watershed area was uniformly patch-cut in openings 5 to 8 tree-heights in diameter. Because field studies have shown that total snow storage is not changed following harvesting, the snowpack was increased 30 percent in the openings and decreased 20 percent in the uncut forest. In addition to redistributing the snowpack to represent the harvesting system, the forest canopy density parameter (C_{dmx}) was reduced to zero on 40 percent of the area in each of 10 hydrologic subunits.

Results obtained through manipulating the input and forest cover parameters in the calibrated model indicated that patch-cutting small openings in mature lodgepole pine and spruce-fir forest results in increased snowmelt early in the melt season with diminished snowmelt later. Although timber cutting affected the timing of snowmelt, it apparently did not significantly change the duration of the snowmelt season. Under comparable conditions, snowmelt began a few days earlier in small openings, but in both the natural forest and cutover areas, the last snow melted out at about the same time. Because melt rates in openings were higher early in the snowmelt season, peak streamflow would not increase appreciably, if at all, under the assumed timber harvesting alternative. Figure 6a summarizes the predicted change in snowmelt input resulting from this practice for the 1947-71 period of record.

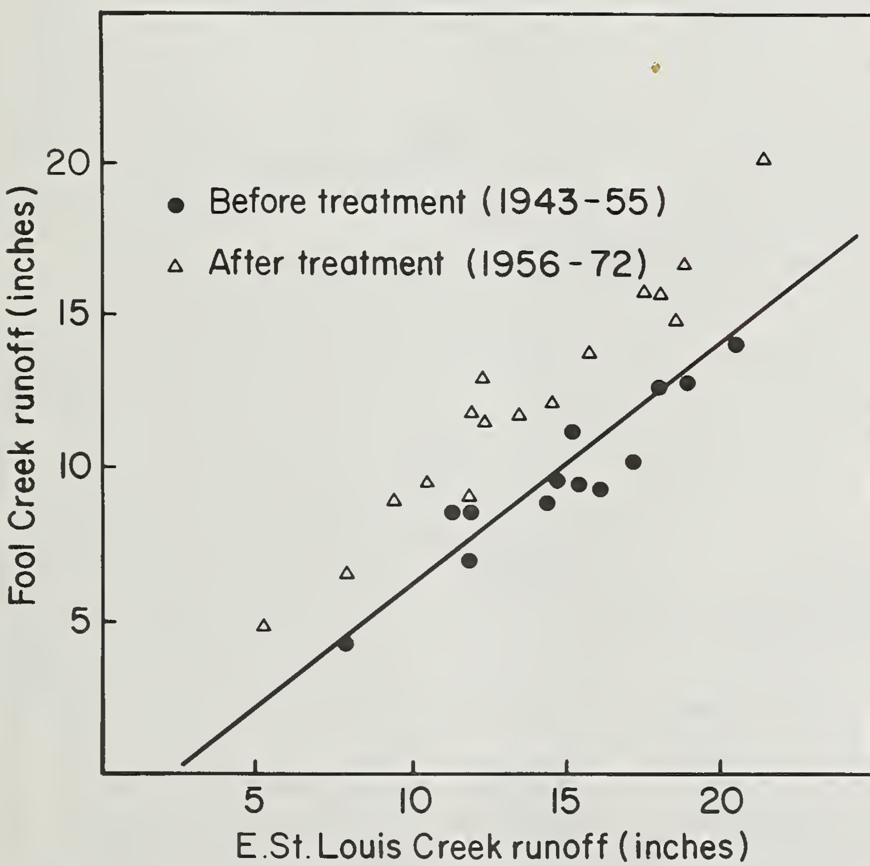
In addition to redistributing the snowpack and accelerating snowmelt runoff, the assumed timber harvesting practice also affected evapotranspiration in two respects. First, during the snow accumulation and melt seasons, evaporation from the snowpack in the small openings was higher, resulting in greater moisture losses than from snow in uncut forest. Secondly, evapotranspiration and interception losses were reduced in

proportion to the amount of forest cover removed. This reduced evapotranspiration resulted in lower soil water deficits on the basin. The net effect was an overall reduction in evapotranspiration and resultant increased water yields. Simulated data for 1947-71 water years are shown in table 1. (Note that with the exception of snowpack water equivalent, all hydrologic components are plotted as 6-day means in fig. 6.)

The simulated average runoff increase for the 1947-71 record period was 2.2 inches, which resulted from a 2.2-inch decrease in evapotranspiration losses, with no change in storage during the average water year. Average soil water requirements on September 30 were decreased by 1.1 inches. As discussed above, snowmelt timing and resultant streamflow were also changed. From figure 6b, it is seen that generated runoff was increased during April, May, and the first part of June and diminished somewhat thereafter. Because the generated flows in figure 6c are routed through natural storage in the watershed to produce the hydrograph, it is reasonable to expect that the recession limb of the seasonal hydrograph would not be significantly changed due to treatment. However, on the rising limb, stream discharges would be higher, as observed from watershed studies in the area.

Table 1.--Simulated hydrologic changes resulting from timber harvesting on Deadhorse Creek, Fraser Experimental Forest (average of 1947-71 water years)

Hydrologic component	Water balance		
	Natural	Treated	Change
	- - *Inches* - -		
Precipitation	30.5	30.5	0
Evapotranspiration	16.8	14.6	-2.2
Soil water recharge requirement			
beginning (10/1)	3.5	2.4	-1.1
end (9/30)	3.5	2.4	-1.1
Water yield	13.7	15.9	+2.2



April - Sept. Runoff Increase Since Harvest

Year	Inches
1956	3.3
1957	5.2
1958	3.7
1959	4.6
1960	5.4
1961	3.4
1962	3.9
1963	2.9
1964	3.5
1965	4.0
1966	2.6
1967	3.1
1968	1.9
1969	2.5
1970	2.1
1971	3.6
1972	3.9
Mean	3.5 ±0.8*

*95 Percent level of confidence

Figure 5. — Pretreatment and posttreatment correlations of seasonal runoff between Fool Creek and adjacent control watershed, Fraser Experimental Forest.

Long-Term Hydrologic Impacts of Timber Harvesting

The model described above has also been used to simulate the long-term effects of forest and watershed management on a 2,461-acre tributary of the South Tongue River in northcentral Wyoming. Pertinent hydrologic characteristics of a typical forested watershed are as follows:

Average maximum snowpack water equivalent	15.5 inches
Average annual precipitation	29.6 inches
Average annual evapotranspiration	15.8 inches
Average annual runoff	13.8 inches

Elevations vary from 8,000 feet msl to 8,900 feet msl. Soils are derived from granitic rocks; virtually all of the forest cover is lodgepole pine. To illustrate how the model was used, results from the analysis of one planning unit will be summarized.

In addition to improving water yield, the management strategy selected for this example essentially has followed recommendations published by Alexander (1972), which

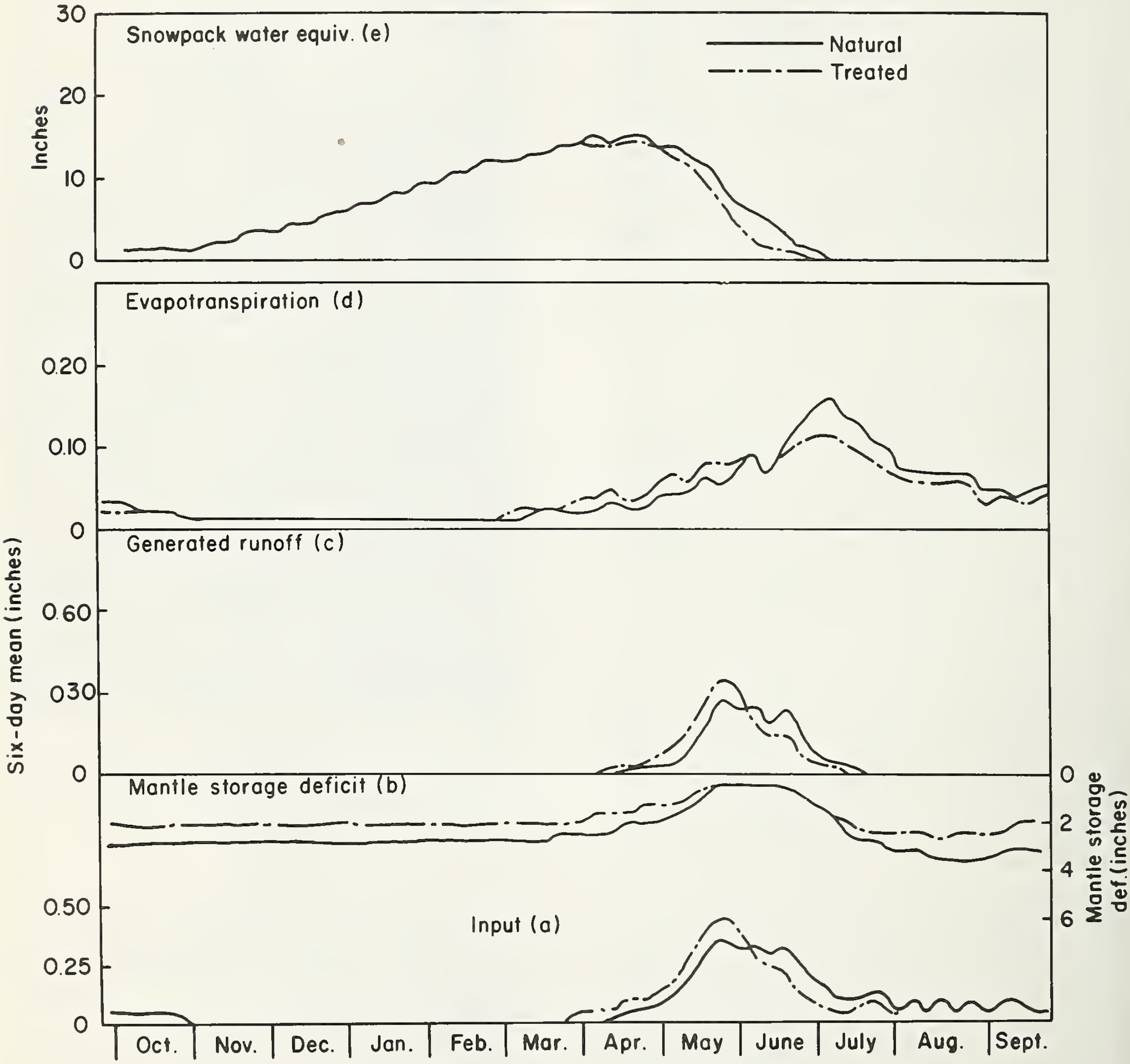


Figure 6. — Simulated average water balance for the 1947-71 water years, showing changes resulting from patch-cutting in mature subalpine forest.

are keyed to stand descriptions, insect and disease problems, and windfall risk situations.

Under this strategy, all of the old-growth timber would be harvested in a series of patch-cuts spread over a planning interval of 120 years. At intervals of 30 years, approximately one-third of the area would be harvested in small openings — five to eight times tree height — distributed over the watershed (table 2). Forest openings would be constructed in a balanced and unified pattern which complements the natural landscape.

Table 2.--Watershed management strategy, South Tongue River planning unit, Bighorn National Forest, Wyoming

Management strategy		Response unit[1]		
		1	2	3
Treatment I				
Patch[2]	1st yr.	X		
Treatment II				
Patch[2]	31st yr.		X	
Thin[3]		X		
Treatment III				
Patch[2]	61st yr.			X
Thin[3]		X	X	
Treatment IV				
Thin[3]	91st yr.	X	X	X

[1]Each unit includes 1/3 of the total area.
[2]33 percent of area occupied by openings which are 5 to 8 tree-heights in diameter.
[3]Thin to $C_{dmx/4}$

As each one-third of the old-growth forest cover on the planning unit is patch-cut, the forest cover density on the previously cutover areas would be reduced to one-fourth of the natural old-growth forest cover density (C_{dmx}). At the end of the planning interval, all of the openings will have regenerated and the watershed would contain groups of trees in several age classes from reproduction to those ready for harvesting on the originally cutover areas. The management strategy would maintain a forest cover throughout the planning interval, and would insure sufficient seed for regeneration from trees cut on the area, or standing around the perimeters of the forest openings.

Projected average annual water yield increases in 10-year increments under this management strategy for the 120-year planning interval are tabulated in table 3. The increases above the heavy diagonal line in table 3 at any given time represent the overall response resulting from preceding management decisions. The data below the line reflect the singular effect of the initial patch-cut on one-third of the planning unit, assuming that it were the final decision in the strategy.

Table 3.--Projected changes in annual water yield resulting from timber harvesting, South Tongue River planning unit, Bighorn National Forest, Wyoming

Interval (years)	Water yield increase, by treatment			
	I	II	III	IV
	- - - - - *Inches* - - - - -			
0-10	1.33			
11-20	1.59			
21-30	0.95			
31-40	0.74	2.08		
41-50	0.61	2.07		
51-60	0.51	1.72		
61-70	0.33		3.37	
71-80	0.08		2.86	
81-90	0.04		2.21	
91-100	-0.03			2.90
101-110				2.29
111-120				1.76

Water yields are improved throughout the planning interval, with the highest increase occurring after Treatment III. Projected runoff increases in relation to the pretreatment base period during each treatment interval are as follows:

Treatment	Runoff Increase Percent
I	9.2
II	14.2
III	20.2
IV	16.8

As seen from table 3, the effect of the initial patch-cut (Treatment I) apparently persists for at least 50, and perhaps 60 or more years. Thereafter, the effect on water yield would for all practical purposes be negligible. (On Fool Creek, in central Colorado, runoff increases have not diminished significantly more than 16 years after strip cutting.)

The projected effects of timber harvesting on the distribution of water available for streamflow are summarized in

table 4. These values represent increments of generated runoff and not routed streamflow. Hence, the effects of watershed storage must be considered in interpreting the data. As seen in table 4, inputs from snowmelt are significantly increased during April and May, and diminished in June. Minor inputs to streamflow apparently also occur in July, while none occur in the natural state due to the less favorable hydrologic condition of the watershed.

Table 4.--Projected changes in distribution of water available for streamflow, South Tongue River, Bighorn National Forest, Wyoming

Month	Natural runoff	Average change in runoff, by treatment			
		I	II	III	IV
	- - - - - - - *Inches* - - - - - - -				
April	0.1	+0.9	+1.2	+1.2	+0.7
May	7.5	+2.0	+2.2	+2.1	+1.3
June	6.2	-2.8	-2.3	-2.7	-1.3
July	0	+0.03	+0.05		

The hydrologic analysis in this example indicated that the magnitude of peak flows would be changed little if at all under the proposed management strategy. However, seasonal peaks would occur approximately one week earlier:

Treatment	Change in peak 7-day generated runoff	Change in timing
	Inches	*Days*
I	-0.3	- 9
II	-0.5	-10
III	-0.3	- 7
IV	+0.3	- 5

To sum up, the projected overall hydrologic impact of the proposed management strategy would be to increase streamflow in April and May each year throughout the 120-year planning interval. This accelerated input would enlarge early spring flows and cause the hydrograph to peak approximately one week earlier than under natural conditions. Hydrograph peaks would apparently not be increased, however, and runoff on the recession side of the hydrograph during the summer months would be slightly diminished.

Discussion

The hydrologic impacts of the watershed management practices discussed above are but two examples of numerous alternatives which have been simulated with the model described in this paper. The model has been tested and calibrated on several representative drainage basins in Colorado and Wyoming. The areas include:

Wyoming: South Tongue River, Bighorn National Forest; East Fork of the Encampment River, Medicine Bow National Forest.

Colorado: Fraser River, Arapahoe National Forest; Wolf Creek, San Juan National Forest.

Timber Models

In addition to improving the water yields in lodgepole pine and spruce-fir forests, it should be emphasized that the strategies selected for water production are compatible with the conversion of old-growth to stands managed from the regeneration period to final harvest for timber production. Yield tables that report probable yields of wood that result from specified combinations of site quality, frequency and intensity of thinning and utilization standards provide goals toward which conversion can be directed. Procedures for deriving yield tables for managed stands and descriptions of the main program and subroutines have been presented for lodgepole pine by Myers et al. (1971) (Program LPMIST) and for spruce-fir by Alexander et al. (1975) (Program SPRYLD). These were adapted from field and computer procedures for managed stand yield tables originally developed by Myers (1971).

These computer programs have the capacity of producing a series of yield tables which show how projected outcomes will vary in response to changes in cultural treatments and/or variations in original stand and site conditions. Large numbers of tables each based on a specific set of alternatives can be computed and printed at the cost of a few cents each. This provides the manager with the opportunity to examine the probable results of his operations, make necessary

changes in management goals, and study the effect of these changes before money is spent on them (Myers 1971).

Linkage Between Hydrologic and Timber Models

The hydrologic model and the timber models (LPMIST and SPRYLD) are linked by means of the forest cover density variable (C_d) as defined previously. Forest cover density is assumed to vary as a function of time according to the expression (eq. [8]):

$$C_d = \frac{C_{dmx}}{\Phi^2}\left(t - t_{c_2}\right)^2 \qquad t_{c_2} \leq t \leq \Phi$$

where

C_d = intermediate forest cover density after cutting is sufficient to reestablish the stand. When $t \leq t_{c_2}$, $C_d = 0.$,

Φ = the time in years from t_{c_2} at which maximum forest cover density is reached. This parameter will vary according to tree species, local environment, and stand condition. and,

C_{dmx} = maximum (natural old growth) forest cover density expressed as a decimal.

In the hydrologic model, logging corresponds to a reduction of the forest cover density (C_d). Thus, the degree that C_d is reduced depends on the relative changes in basal area. As stated previously, in old-growth stands, if C_d is reduced by 50 percent or less from C_{dmx}, it is assumed that forest cover density does not increase subsequent to cutting. However, if C_d is reduced more than 50 percent from C_{dmx}, but not clearcut, equation [8] is used to simulate redevelopment of the canopy with time. In the event that C_d is reduced to zero (clearcut), Φ is replaced by a new parameter, Φ' in equation [8], which then computes redevelopment of the canopy with time under "managed stand" conditions.

No relationship has been established between C_d and basal area, average diameter, and site index. However, calibration studies indicate it is reasonable to assume that a given percentage reduction in cover density corresponds reasonably well to a similar reduction in basal area. Comparisons between basal area levels after patch-cutting and forest cover density are summarized for a specified set of stand conditions in table 5.

Table 5.--Comparisons of basal area[1] after initial clearcutting with forest cover density

Years since initial cut	Basal area (ft^2/ac)		Forest cover density (C_d)	
	Before	After	Before	After
	Lodgepole pine (ϕ' = 30 years)			
0	130	0	0.30	0
30	110	61	.30	0.16
60	129	92	.30	.21
90	146	100	.30	.21
120	146	0	.30	0
	Spruce-fir (ϕ' = 60 years)			
0	325	0	.55	0
50	94	63	.38	.24
80	153	99	.55	.35
110	176	100	.55	.31
140	160	0	.55	0

[1]Basal areas for lodgepole pine computed from Program LPMIST for site index 60, and initial and subsequent growing stock levels of 100.

Basal areas for spruce-fir computed from Program SPRYLD for site index 80, and initial and subsequent growing stock levels of 100.

Applications

Lodgepole Pine. — The management strategy (table 6) is similar to that in table 2 for the Bighorn National Forest, but for another area in central Colorado.

Similar to the watershed management strategy in the previous example, water available for streamflow on each response unit is substantially increased by the patch-cutting of lodgepole pine (table 7, fig. 7). In the cleared areas, the increase in water available for streamflow is maintained at a higher level by frequent intermediate thinnings throughout the rotation than if the forest was allowed to return to preharvest conditions naturally. Figure 8 shows projected water yield changes from initial patch-cutting and subsequent thinning on one response unit. In the example used here, the forest manager also wishes to determine the growing stock

levels that will maximize volume production in board feet within the limits imposed by the cutting strategy for water production. Since water yield is unaffected by site quality, an average site index (60) has been chosen. Furthermore, simulation analyses indicate that water yields are little affected by any combination of initial and subsequent growing stock levels in managed stands that range from ≤ 80 to ≥ 120 ft²/ac. Length of rotation is 120 years with a 30-year cutting cycle. Alternatives that call for more than one precommercial thinning are unacceptable. Minimum commercial volumes per acre are 400 cubic feet and 1500 board feet. The manager expects that his procedures for regenerating each patch-cut will result in a new stand that contains 1,000 trees per acre by age 30, with an average stand diameter of 4.5 inches. Furthermore, dwarf mistletoe infection will not occur during the life of the stand.

Table 6.--Watershed management strategy for lodgepole pine, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado[1]

Management strategy		Response unit 1	2	3
Treatment I				
Patch[2]	1st yr.	X		
Treatment II				
Patch[2]	31st yr.		X	
Thin[3]		X		
Treatment III				
Patch[2]	61st yr.			X
Thin[3]		X	X	.
Treatment IV				
Thin[3]	91st yr.	X	X	X
Treatment V				
Harvest[2]	121st yr.	X		
Thin[3]			X	X

[1]Aspect: SSE
Elevation: 10,500 ft. msl
Slope: 30 percent
[2]33 percent of the area cut in openings 5 to 8 times tree height.
[3]Thin to growing stock levels specified under section on Timber Management Alternatives.

A few of the yield tables produced by LPMIST are reproduced in Appendix A. For the situation described above, yields and number of precommercial thinnings are of greatest interest. These items are summarized in tables 8 and 9 for the 9 yield tables produced. Only the combination of low initial and low subsequent growing stock levels meets the requirement of only one precommercial thinning.

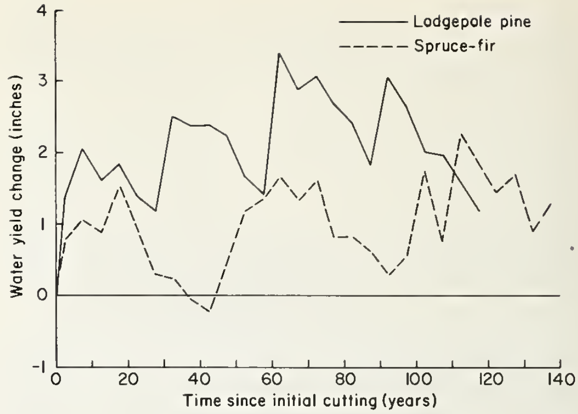


Figure 7. — Projected water yield changes from management strategies outlined in tables 7 and 11.

Table 7.--Projected changes in annual water yield resulting from tiber harvesting in lodgepole pine, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado

Interval (years)	Water yield increase, by treatment I	II	III	IV
	Inches			
0-10	1.72			
11-20	1.73			
21-30	1.29			
31-40		2.44		
41-50		2.30		
51-60		1.54		
61-70			3.12	
71-80			2.86	
81-90			2.11	
91-100				2.84
101-110				1.98
111-120				1.38

Additional comparisons can be made to include such factors as probable thinning costs, cubic yields from thinnings not commercial for board feet, and the average size of tree produced. As expected, the current crop produces more board feet in 120 years at high subsequent levels of growing stock, but two precommercial thinnings would be required.

Spruce-fir. — Water available for streamflow on each response unit is also substantially increased by patch-cutting spruce-fir in small openings 5 to 8 times tree height according to the management strategy outlined in table 10 (table 11, fig. 7). However, on the cleared areas, water

available for streamflow decreases after the initial cutting at about the same rate whether or not intermediate thinnings are made throughout the rotation. This is illustrated by figure 9, which shows projected water yield changes from initial patch-cutting and subsequent thinning on one response unit compared with no thinning after initial harvest. There are, however, other advantages to thinning spruce-fir. Growth is concentrated on fewer stems, and total yields of usable products are increased. In the example here, the forest manager also wishes to determine the growing stock levels that will maximize volume production in board feet within the limits imposed by the watershed management strategy. Water yields are little affected in spruce-fir forests by either site quality or the growing stock levels that are likely to be timber management goals. An average site index of 80 was chosen. Length of rotation is 120 years (breast height age) with a 30-year cutting cycle.[2] Alternatives that call for more than one precommercial thinning are unacceptable. Minimum commercial volumes per acre are 400 cubic feet and 2,000 board feet. The manager expects that his procedure

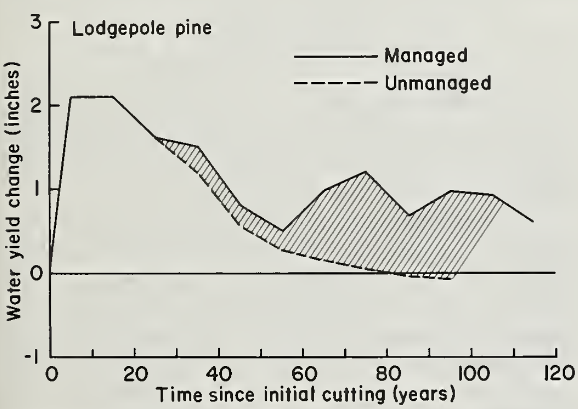


Figure 8. — Projected water yield changes for managed (all options) and unmanaged lodgepole pine following initial patch-cutting on one response unit. Cutting cycle 30 years; site index 60 feet; all initial and subsequent stocking levels likely to be timber management goals.

[2]Age in SPRYLD is age at breast height. The 50-year interval between patch-cutting and the first thinning in table 11 is to allow a minimum of 20 years for spruce and fir trees to regenerate and grow to 4.5 feet in height. A 120-year rotation is therefore at least 140 years in the total age of the stand.

for regenerating each patch-cut will result in a new stand that contains 850 trees per acre with an average stand diameter of 4.5 inches by b.h. age 30 years.

Table 8.--Number of precommercial thinnings based on minimum board feet volumes, if each of the 9 combinations of initial and subsequent growing stock levels is executed as specified by the data decks for spruce-fir (SPRYLD) and lodgepole pine (LPMIST)

Initial thinning basal area level (ft²/ac)	Subsequent basal area level (ft²/ac)		
	80	100	120
Spruce-fir (Program SPRYLD)			
80	1	2	2
100	1	1	2
120	1	1	2
Lodgepole pine (Program LPMIST)			
80	1	2	2
100	2	2	2
120	2	2	2

Table 9.--Yields in thousand board feet, including commercial thinning of 9 combinations of initial and subsequent growing stock levels, spruce-fir and lodgepole pine

Initial thinning basal area level (ft²/ac)	Subsequent basal area level (ft²/ac)		
	80	100	120
Spruce-fir (Program SPRYLD)			
80	32.7	36.2	41.3
100	33.3	37.4	40.6
120	33.5	37.6	40.4
Lodgepole pine (Program LPMIST)			
80	24.2	25.0	27.5
100	21.0	24.8	27.3
120	20.8	24.0	27.0

A few of the yield tables produced by SPRYLD are reproduced in Appendix B. For the situation described above, yields and number of precommercial thinnings are summarized in tables 8 and 9 for the 9 tables produced. The combination of high initial and intermediate subsequent growing stock levels produces the greatest volume with one precommercial thinning.

Comparisons can also be made to include thinning costs, cubic yields from thinnings not commercial for board feet and the average size of tree produced. The current crop

produces more board feet with the combination of low initial and high subsequent growing stock levels, but two precommercial thinnings will be required.

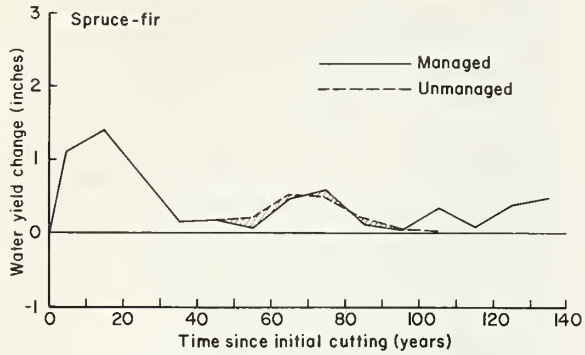


Figure 9. Projected water yield changes for managed (all options) and unmanaged spruce-fir following initial patch-cutting on one response unit. Cutting cycle 30 years (50 years initial cut); site index 80 feet; all initial and subsequent stocking levels likely to be timber management goals.

Table 10.--Watershed management strategy for spruce-fir, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado[1]

Management strategy		Response unit		
		1	2	3
Treatment I				
Patch[2]	1st yr.	X		
Treatment II				
Patch[2]	51st yr.		X	
Thin[3]		X		
Treatment III				
Thin[3]	81st yr.	X		
Treatment IV				
Patch[2]	101st yr.			X
Thin[3]			X	
Treatment V				
Thin[3]	111th yr.	X		
Treatment VI				
Thin[3]	131st yr.		X	
Treatment VII				
Harvest[2]	141st yr.	X		

[1]Aspect: NE
Elevation: 10,200 ft. msl
Slope: 35 percent
[2]33 percent of the area cut in openings 5 to 8 times tree height.
[3]Thin to growing stock levels specified under section on Timber Management Alternatives. Yield tables for spruce-fir are based on breast height age. On a 30-year cutting cycle a minimum of 20 additional years will be required for trees to reach breast height.

Table 11.--Projected changes in water yield resulting from timber harvesting in spruce-fir, Deadhorse Creek planning unit, Fraser Experimental Forest, Colorado

Interval (years)	Water yield increase, by treatment			
	I	II	III	IV
	- - - - - *Inches* - - - - -			
0-10	0.91			
11-20	1.20			
21-30	.64			
31-40	.10			
41-50	.10			
51-60		1.26		
61-70		1.49		
71-80		1.21		
81-90			0.71	
91-100			.42	
101-110			1.22	
111-120				2.06
121-130				1.54
131-140				1.09

Summary

The following paragraphs highlight the practical aspects of this work, and summarize important principles which should be considered in land use planning.

• Highest water yields result when old-growth subalpine forests are harvested in small patches. When forest openings are: (1) less than 8 tree-heights in diameter; (2) protected from wind, and (3) interspersed so that they are 5 to 8 tree-heights apart, an optimum pattern of snow accumulation results. More snow is deposited in the openings, and less snow accumulates in the uncut forest so that total snow on headwater basins is not significantly increased.

• Snowmelt in the small openings on all aspects is more rapid than in the uncut forest. This accelerated melt causes streamflow to be higher on the rising limb of the hydrograph than before harvest cutting. When there is considerable natural regulation in the form of deep porous soils, recession flows should not be changed appreciably and annual flood peaks are not significantly increased provided that the forest cover on no more than 50 percent of the watershed is removed in a system of small openings.

• Simulation analyses indicate that under a patch-cut alternative, water yield increases on south slopes are at least as large as corresponding increases from north aspects. Hence, there is no reason to favor areas with the highest natural water yield if the objective is to maximize water yield from old-growth subalpine forests.

• Due to the considerable length of time that it takes for subalpine coniferous forests to regenerate, increased water yields from patch-cutting can go undiminished for 30 years and longer. Even after this period of time, it is conceivable that 30 additional years will be required before runoff increases from the initial timber harvest are completely erased.

• It should be emphasized that the *pattern* in which trees are harvested determines whether or not runoff will be increased. For example, when the forest cover is removed in large clearcut blocks or by selective cutting of individual trees, increased water yields will be far less than that attained if the same volume of timber is harvested in a system of small dispersed forest openings. Under some conditions, streamflow may actually be decreased when timber is selectively harvested or clearcut in large blocks.

• In much of the Rocky Mountain Region, timber harvesting which produces the most additional water is ecologically sound. If done properly, it does not reduce water quality; it is a silviculturally acceptable procedure and compatible with the guidelines recently developed from research in old-growth subalpine forests (Alexander 1972, 1973, 1974). The strategies selected for optimum water production are compatible with the conversion of old-growth to stands managed from the regeneration period to final harvest for timber production.

• Procedures are available for projecting long-term yields of both wood and water resulting from a broad array of management alternatives. This capability provides the manager with the opportunity to examine the probable results of his operations within the context of multi-resource management.

Conclusion

One of the major shortcomings of the models described in this paper is the lack of sufficient data for validation, particularly with respect to man's long-term impacts on the timber and water resources. Nevertheless, the models produce expected results based on experience and the state-of-the-art. It is believed that the output from the examples above contain the type of information which hydrologists, silviculturalists, and land use planners need to know in order to make difficult management decisions. The ability of the models described in this paper and other similar models to integrate complex forest and water systems make them unique and powerful tools for evaluating a broad array of land management alternatives.

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Appendix A
Typical Yield Tables Produced by LPMIST

YIELDS PER ACRE OF EVEN-AGED STANDS OF LODGEPOLE PINE
SITE INDEX 60
THINNING INTENSITY- INITIAL- 80. SUBSEQUENT- 80.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	1000	110	4.5	24	1270	170	0					
30	325	50	5.3	26	630	170	0	675	60	640	0	0
40	322	72	6.4	32	1160	720	0					
50	321	93	7.3	36	1670	1340	0					
60	321	115	8.1	42	2420	2120	8700					
60	185	76	8.7	43	1650	1490	6100	136	39	770	630	2600
70	182	91	9.6	48	2220	2050	8600					
80	179	106	10.4	52	2790	2620	11100					
90	179	122	11.2	56	3480	3280	14200					
90	104	80	11.9	57	2280	2160	9600	75	42	1200	1120	4600
100	104	93	12.8	60	2740	2600	11800					
110	104	106	13.7	63	3240	3090	14300					
120	104	119	14.5	65	3730	3560	16800					

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 120. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 6.5 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF EVEN-AGED STANDS OF LODGEPOLE PINE
SITE INDEX 60
THINNING INTENSITY- INITIAL- 120. SUBSEQUENT- 120.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	1000	110	4.5	24	1270	180	0					
30	505	72	5.1	25	880	180	0	495	38	390	0	0
40	502	99	6.0	32	1540	760	0					
50	500	122	6.7	35	2140	1540	0					
60	498	145	7.3	41	2990	2410	0					
60	322	107	7.8	42	2250	1920	0	176	38	740	490	0
70	322	127	8.5	47	3010	2700	11100					
80	322	145	9.1	52	3770	3470	14300					
90	321	165	9.7	55	4580	4240	17900					
90	207	120	10.3	56	3370	3170	13300	114	45	1210	1070	4600
100	207	137	11.0	59	4070	3840	16500					
110	207	152	11.6	62	4670	4410	19400					
120	207	168	12.2	64	5300	5020	22400					

DWARF MISTLETOE INFECTION DID NOT OCCUR DURING THE ROTATION OF 120. YEARS.

MERCH. CU. FT. - TREES 6.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 6.5 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

Appendix B
Typical Yield Tables Produced by SPRYLD

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 80., SUBSEQUENT - 80.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	314	52	5.5	29	680	340	0	536	42	330	0	0
40	311	78	6.8	38	1260	900	0					
50	305	106	8.0	45	2030	1650	4200					
60	295	133	9.1	53	2920	2530	8300					
60	149	80	9.9	53	1810	1610	5700	146	53	1110	920	2600
70	145	99	11.2	59	2510	2310	9200					
80	145	122	12.4	65	3370	3150	13600					
90	145	146	13.6	70	4350	4120	18700					
90	55	80	16.3	71	2440	2340	11100	90	66	1910	1780	7600
100	55	95	17.8	75	3000	2910	14500					
110	55	112	19.3	79	3610	3520	18300					
120	55	130	20.8	82	4290	4200	22500					
						TOTAL YIELDS				7640	6900	32700

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

YIELDS PER ACRE OF MANAGED, EVEN-AGED STANDS OF ENGELMANN SPRUCE AND SUBALPINE FIR

SITE INDEX 80, 30-YEAR CUTTING CYCLE

THINNING LEVELS= INITIAL - 120., SUBSEQUENT - 120.

ENTIRE STAND BEFORE AND AFTER THINNING								PERIODIC INTERMEDIATE CUTS				
STAND AGE (YEARS)	TREES NO.	BASAL AREA SQ.FT.	AVERAGE D.B.H. IN.	AVERAGE HEIGHT FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.	TREES NO.	BASAL AREA SQ.FT.	TOTAL VOLUME CU.FT.	MERCHANT-ABLE VOLUME CU.FT.	SAWTIMBER VOLUME BD.FT.
30	850	94	4.5	28	1010	340	0					
30	505	72	5.1	29	870	340	0	345	22	140	0	0
40	498	108	6.3	37	1620	1050	0					
50	485	141	7.3	45	2540	1940	0					
60	466	175	8.3	52	3660	3040	8700					
60	259	117	9.1	52	2570	2230	7300	207	58	1090	810	1400
70	249	141	10.2	59	3480	3130	11800					
80	249	173	11.3	64	4680	4300	17800					
90	249	205	12.3	69	5960	5570	24400					
90	103	120	14.6	70	3600	3430	15900	146	85	2360	2140	8500
100	103	142	15.9	75	4540	4360	20900					
110	103	166	17.2	78	5410	5220	26300					
120	103	190	18.4	82	6310	6120	31900					
						TOTAL YIELDS				9900	9070	40400

MINIMUM CUTS FOR INCLUSION IN TOTAL YIELDS-- 400. CUBIC FEET AND 2000. BOARD FEET

MERCH. CU. FT. - TREES 5.0 INCHES D.B.H. AND LARGER TO 4-INCH TOP.

BD. FT. - TREES 8.0 INCHES D.B.H. AND LARGER TO 6-INCH TOP.

Leaf, Charles F., and Robert R. Alexander.
1975. Simulating timber yields and hydrologic impacts resulting from timber harvest on subalpine watersheds. USDA For. Serv. Res. Pap. RM-133, 20 p. Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo. 80521.

A dynamic simulation model determines the hydrologic changes resulting from timber harvesting, and correlary models simulate timber yields. Emphasis is placed on the "planning unit" which is defined by environmental characteristics, including combinations of slope, aspect, elevation, and forest cover. The models are intended for use on subalpine watersheds where the primary source of streamflow is melting snow. The hydrologic model simulates winter snow accumulation, short- and longwave radiation balance, snowpack condition, snowmelt, and subsequent runoff in time and space. The timber models simulate projected timber yields in response to changes in cultural treatments and/or variations in original stand and site conditions.

Keywords: Computer models, forest management, simulation analysis, hydrology, watershed management.

Leaf, Charles F., and Robert R. Alexander.
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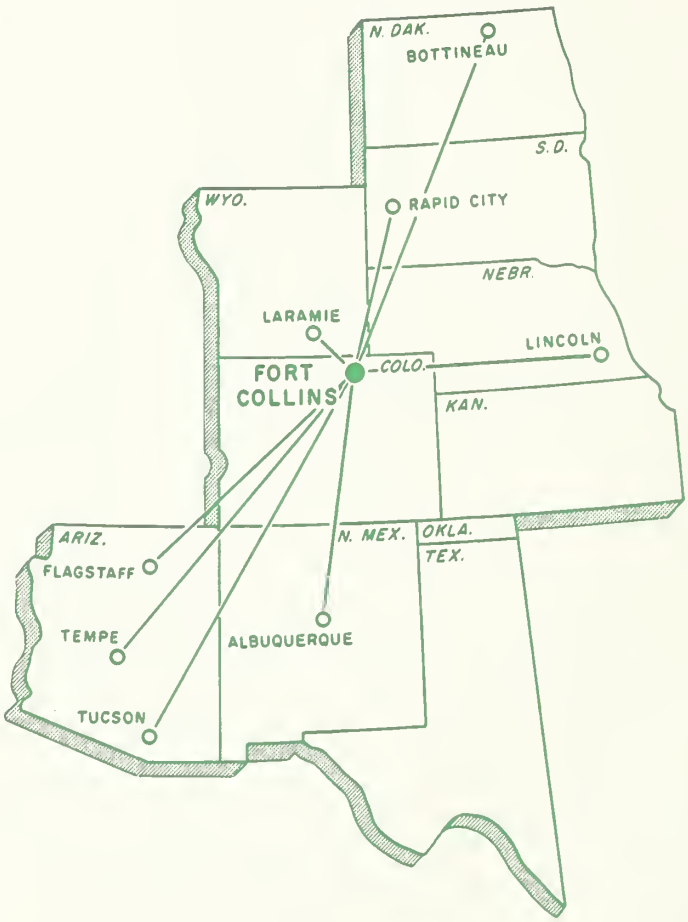
N. DAK.
BOTTINEAU
S.D.
WYO.
RAPID CITY
NEBR.
LARAMIE
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KAN.
ARIZ.
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TUCSON